



## **Rapid Prototyping - From Concept to Reality - Application for the Design Optimization of Superconducting Magnet End Parts Using Selective Laser Sintering**

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**Abstract**—*This note describes the use of a cost-efficient rapid prototyping technique-selective laser sintering -for making prototype end parts.*

### **1. Introduction**

The performance of the superconducting magnets is often limited by their ends. The end parts used to confine the superconducting cable at their ends cost a significant fraction of the overall cost of a magnet. The design and fabrication of these end parts is a very involved and a time-intensive process. Therefore, an effort is underway at Fermilab to find ways to reduce the cost and design & fabrication time for magnet end parts.

A Rutherford-type cable has been widely used to build accelerator-type cosine-theta magnets. This cable is composed of superconducting wires that are twisted around a core and then pressed into a keystone shape. As the cable is formed around the magnet end parts during coil winding, dekeystoning of the cable is observed along with an accompanying increase in the cable mid-thickness. A-priori quantitative knowledge of this cable shape change is necessary for designing end parts in a way such that the conductors are well confined at magnet ends without any significant gaps. At present, there is a good understanding of the cable shape change parameters for the widely used NbTi cable with kapton insulation [1]. However, such an understanding is lacking for the Nb<sub>3</sub>Sn cable with advanced ceramic or glass fiber insulation that is required to withstand the high reaction temperature. Further, a change in the cable dimensions has been observed for the Nb<sub>3</sub>Sn cable after reaction. Therefore, the design of optimized end parts is an iterative process for the Nb<sub>3</sub>Sn cable with advanced insulation. Rapid Prototyping (RP) techniques such as selective laser sintering can help to cut down this design

optimization time by allowing one to fabricate end parts in a very short time and for a very economical price.

## 2. Results

*Program File:* To reduce the end parts design time, **a program file has been developed that takes BEND's output data and generates 3-dimensional solid models of all the different end parts (such as the key, spacer, and saddle) automatically.** This program file is executed within the I-DEAS solid modeling program. Further details of this program file would be provided in a separate technical note\*. This automatic generation of 3-d solid models offers a very significant saving in time and allows one to visualize different variants of the design quickly. Further, Rapid Prototyping techniques such as the selective laser sintering could be used to make prototype end parts, using the solid models generated in I-DEAS, at a very economical price and in an extremely short time. Test coils could be wound using these prototype parts and the results from test coil windings can be incorporated in a further design optimization.

*Selective Laser Sintering:* "The selective laser sintering station (SLS) uses a plastic powder to create prototype parts. The powder is melted, layer by layer, by a computer-directed heat laser. Additional powder is deposited on top of each solidified layer and again sintered." Fig. 1 shows a photograph of an SLS machine and Fig.2 shows some parts made out of powder using this machine. "SLS allows for the most diversity in material selection, including nylon, glass-filled nylon, SOMOS (rubber-like) and Truform (investment casting). Also available is a new polyamide nylon material called Duraform and copper Duraform for direct tooling. The SLS process provides the most functional rapid prototype available.+" Fig. 3 and 4 show photographs of the inner and outer layer end parts made using this process for a test coil winding.

*Test Coil:* A test coil, PC03 has been wound and cured using laser sintered end parts made out of copper (80%)-duraform (20%) and with a Nb<sub>3</sub>Sn cable (ITER conductor produced by New England Electric Company) wrapped with an S2 glass insulation. This coil was cured at 125 °C for 1 hour instead of the usual 150 °C cure for 30 minutes. Fig. 5 and 6 show photographs of the cured inner and outer layers. Fig. 7 and 8 show the top and bottom views of the cured inner layer lead end. Similar views for the cured inner layer return end are provided in Fig. 9 and 10. Fig. 11 and 12 show the top view of the cured outer-layer lead and return ends respectively. It is clear that *the quality of the coil winding is excellent* and that *the conductor is well confined around the end parts*. No large gaps between the conductors and end spacers, observed in some of our previous coil windings, are seen for the laser sintered end parts. A comparison of the sectioned ends for the laser sintered parts and the parts fabricated previously using wire EDM would be presented in a future technical note.

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\* It should be noted that 3-d solid models of the end parts and the conductor would allow one to perform a coupled magnetic and thermo-mechanical analysis of the coil ends to understand better the magnet end mechanics and its quench behavior.

+ from Conceptual Reality's website.

*Cost Issues:* It should be noted that the price paid for the 21 end parts used in PC03 winding was \$2,850, which is expected to come down further with competitive bidding and vendor experience. In contrast, conventional 5-axis milling of the same parts can cost anywhere between \$12,000 to \$15,000 due to the associated programming, set-up and tooling costs. Therefore, selective laser sintered end parts are a much more viable option for the design optimization studies and to get prototype parts fabricated at a very economical price and in the shortest possible time. Further work is still necessary to find suitable Rapid Prototyping techniques that can reduce the cost of fabrication for the real magnet end parts. However, with rapid advances in the RP technology, the outlook looks very promising.

### **3. Summary**

We have shown that Rapid Prototyping techniques such as selective laser sintering (SLS) provide a very useful tool for the end parts design optimization studies. SLS allows one to fabricate prototype end parts at a very economic price and in a very short time.

### **Reference:**

1. J.S. Brandt, "Coil End Design for the LHC Dipole Magnet," FERMILAB-TM-1954, Fermilab, Batavia, IL, May 1996.



**Figure 1: SLS machine (photo from Conceptual Reality website).**



**Figure 2: SLS parts out of machine (photo from Conceptual Reality website).**



**Figure 3: Selective Laser Sintered End Parts for Inner Layer.**



**Figure 4: Selective Laser Sintered End Parts for Outer Layer.**

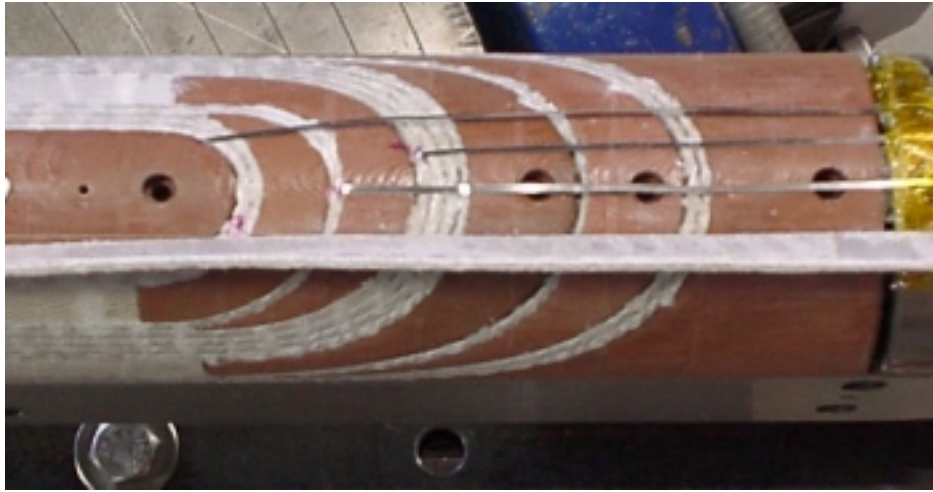


**Figure 5: Cured Inner Coil, PC03 wound using Selective Laser Sintered End Parts.**

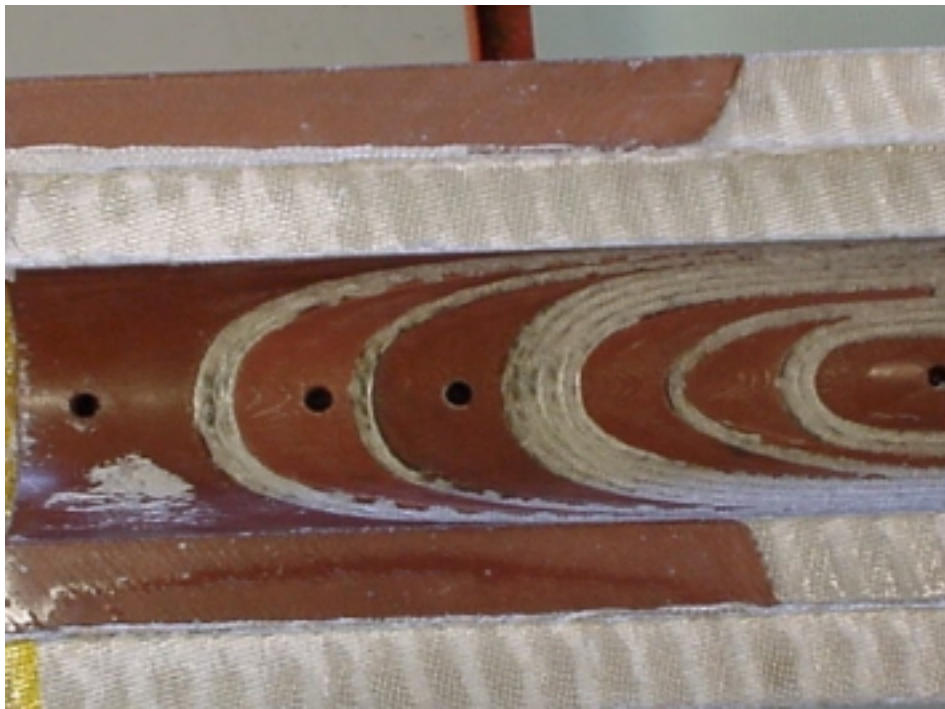


**Figure 6: Cured Outer Coil, PC03 wound using Selective Laser Sintered End Parts.**

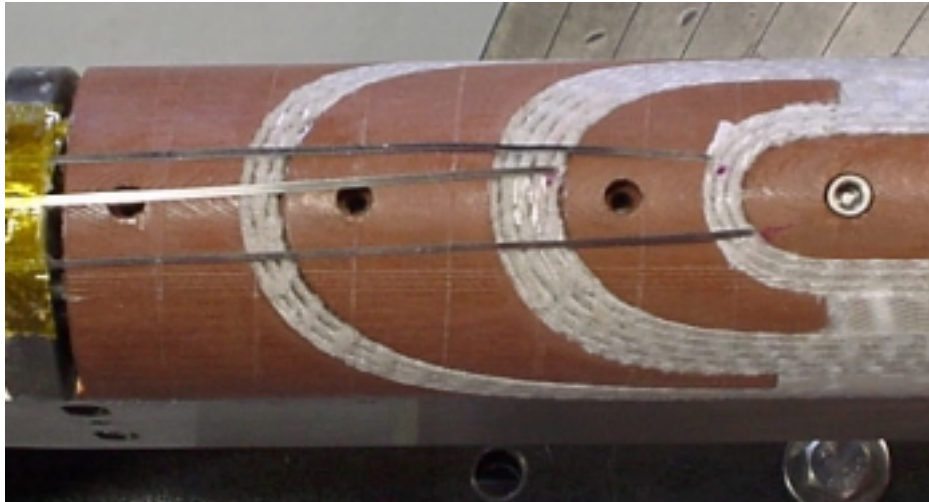




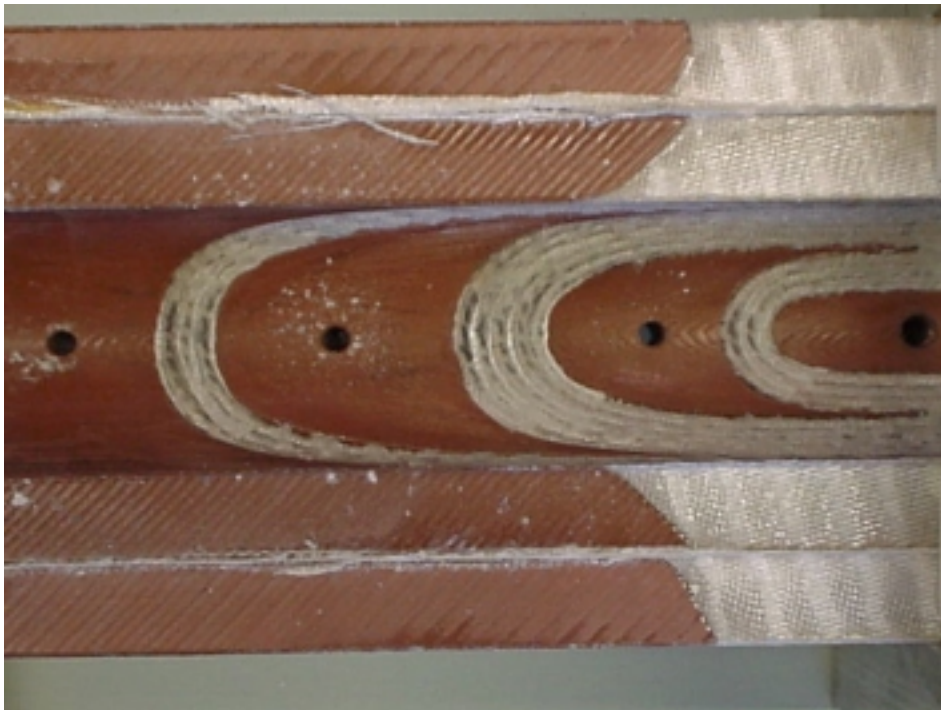
**Figure 7: Close up top view of the Lead End of the cured Inner Layer for PC03.**



**Figure 8: Close up bottom view of the Lead End of the cured Inner Layer for PC03.**



**Figure 9: Close up top view of the Return End of the cured Inner Layer for PC03.**

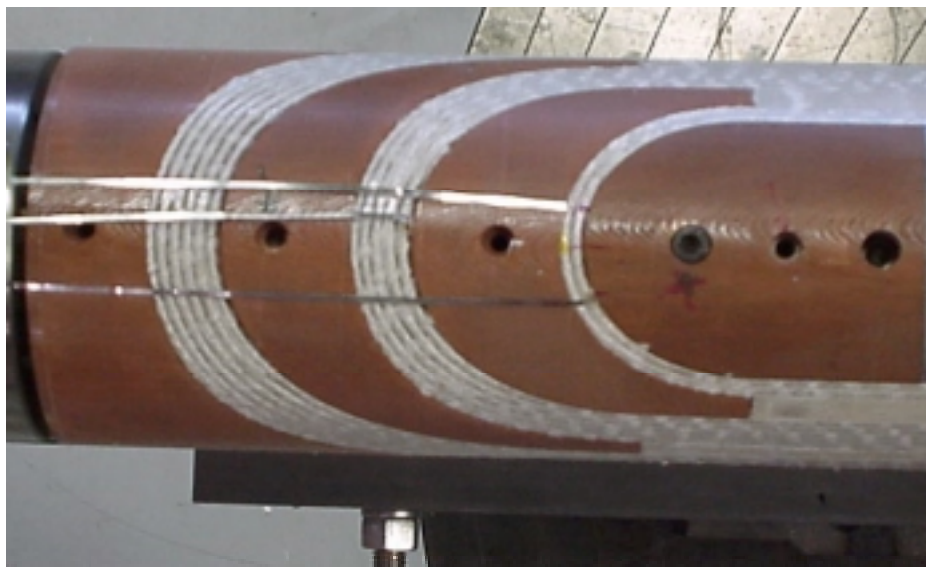


**Figure 10: Close up bottom view of the Return End of the cured Inner Layer for PC03.**





**Figure 11: Close up top view of the Lead End of the cured Outer Layer for PC03.**



**Figure 12: Close up top view of the Return End of the cured Outer Layer for PC03.**